Micro-nanoplastics in the Environment: Current Research and Trends

Prodipto Bishnu Angon, Shitosri Mondal, Arpan Das, Md. Shakil Uddin, and Afsana Ahamed Eva

1 Introduction

Researchers and policymakers are increasingly challenged by the growing environmental implications of micro-nanoplastics (MNPs), which are being generated, dispersed, and accumulated worldwide (Kumar, 2020; Xu et al., 2020). Recently, this problem has received a lot of attention from scientific communities as well as governing bodies. Microplastics (MPs) (less than 5 mm) and nanoplastics (NPs) (typically deemed less than 1000 nm) are also a source of worry, in addition to the more obvious macroplastics (Kukkola et al., 2021). Over the last 50 years, the world has created an estimated 9200 million metric tons of plastic, marking a 20-fold increase in plastic manufacturing (Walker & Fequet, 2023). More than 6900 metric tons were dumped in landfills or, worse, added to pollutants in the environment (Brooks et al., 2018; Geyer et al., 2017). About 368 million metric tons of plastic were manufactured globally in 2019, but in the upcoming 20 years, that number has been predicted to quadruple (Walker & Fequet, 2023). The fact that most consumer plastics are made for single use and have little recyclability is partly to blame for the rise in global production and consumption that has led to record-breaking accumulations of plastic rubbish and widespread plastic pollution (Borrelle et al., 2020). Only around 9% of all plastic trash in the world has ever been recycled; another 12% has been burned, and the other 79% has accumulated in ecosystems (Geyer et al., 2017).

A significant source of MNP contamination is the usage of agricultural plastic items, which is why agricultural areas are regarded as a primary sink of MNPs (Huang et al., 2020). An estimated 12.5 million tons of plastic are utilized in agricultural production globally, of which 310,000 tons are used exclusively for crop cultivation (Zantis et al., 2023). The agriculture and horticultural industries

P. B. Angon (✉) · S. Mondal · A. Das · M. S. Uddin · A. A. Eva
Faculty of Agriculture, Bangladesh Agricultural University, Mymensingh, Bangladesh

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annually discharge between 5400 and 23,500 tons of MPs into the environment (Zantis et al., 2023). Another significant MNP pollution source is the spread of biosolids, or treated sludge, from wastewater treatment facilities on agricultural fields (Kallenbach et al., 2022). The number of MPs discharged from sewage sludge onto agricultural areas varies between 44,000 and 300,000 tons in North America and 63,000 and 430,000 tons in Europe (Nizzetto et al., 2016). Nonfarming activities, such as the use of landfills, littering (e.g., discarded tires and other materials), and air deposition, all contribute to an increase in soil contamination (Yadav et al., 2020).

MNPs may alter soil structure in agricultural fields, which may then have an impact on many creatures, including plants. MNPs are capable of being absorbed by plant roots and leaves (Sun et al., 2021). The trophic transfer along the food chain, from soil to organisms and people, has consequently caused worry (Beriot et al., 2021). Additionally, toxicological consequences have been noted in plants exposed to MNPs, including metabolic reactions and effects on growth performance (Colzi et al., 2022). However, reactions differ significantly between research. For instance, MNPs had a detrimental impact on the germination rate of cress but had no discernible impact on wheat (*Triticum aestivum* L.) or maize (*Zea mays* L.) (Gong et al., 2021). In addition to species-specific reactions, factors like the number, type, shape, and size of MNPs might affect the outcomes. For instance, different MNP types and shapes will have different impacts on plant development, and different MNP sizes will have different effects on enzyme activities (Zantis et al., 2023).

Recently, a number of reviews and studies that explore the incidence and destiny of MNPs in natural environments have been published (Kumar, 2020; Wang et al., 2019). Researchers looked at marine MPs, and it has been well established that they exist in coastal areas (Aslam et al., 2020; Kane & Clare, 2019). Another possible sink for MPs is the freshwater system (Strungaru et al., 2019). Recent agricultural intensification and plastic landfilling methods have drawn MPs' attention to the pollution of terrestrial ecosystems, which includes agricultural soil (Wang et al., 2019). Recently, it was estimated and observed that MPs occur in the terrestrial environment 4–23 times more frequently than in the marine environment (Horton, Walton, et al., 2017). A wide variety of concentrations of MPs were examined in industrial soils (L. Li et al., 2020), home garden soil, agricultural soil (Liu et al., 2018), floodplain soil (Scheurer & Bigalke, 2018), and coastal soil. The presence of MPs in terrestrial soils demonstrates a range of environmental consequences for the soil's flora and fauna, as well as toxicity (de Souza Machado et al., 2018; Rillig et al., 2019). MPs' contaminated soil had a detrimental effect on how native flora and the soil microbial ecosystem functioned. A further significant finding is that MPs are taken up by plants (crops), reaching a higher trophic level and having a greater negative effect (Sun et al., 2020).

NPs are produced from impregnated or manufactured nanoparticles or when larger plastic waste materials break down (Ferreira et al., 2019). The smaller-sized unit of MPs known as NPs has recently attracted more interest (Wagner & Reemtsma, 2019). NPs pose more danger than MPs due to their ease of entry into cells and tissues. The complexity of NP separation and identification, as well as their abundance in the environment, has mainly gone unnoticed until now. Therefore, it is possible

that NPs' physical threat to human health is underestimated. A recent field of study in the environmental sciences is NPs. Clarifying the toxicological effects and mechanism of action of the neoplastic will require more study in this area.

Diverse sources of MNPs provide significant hazards to ecosystems, human health, plants, and aquatic life. MNPs enter the environment through improper waste management, contributing to pollution in the air, water bodies, and soils. In aquatic ecosystems, MNPs pose risks to marine life by causing physical harm, affecting feeding behavior, and facilitating the transfer of toxins through the food chain. Additionally, MNPs can disturb aquatic plants' growth and photosynthetic processes. Human exposure occurs through ingestion, inhalation, and skin contact, raising concerns about their impacts on health, including inflammation, DNA damage, and endocrine disruption, with potential links to cancer and neurological disorders. MNPs can impact plant traits such as growth, chlorophyll content, and root development. Research gaps regarding MNPs might include the study of nonspherical MNPs, the influence of aged particles, terrestrial pollution implications, and comprehensive ecosystem interactions. Urgent global efforts are needed to address MNP contamination, as plastic production continues to outpace recycling and waste reduction attempts. Though efforts to reduce plastic wastes are underway, they lag behind production rates. Addressing MNP contamination necessitates an overhaul of the global plastics value chain, demanding the collaboration of governments, industries, and individuals. Collective action is essential to mitigate pollution, curb plastic use, and ensure a sustainable future. The authors jointly refer to MPs and NPs in this chapter as MNPs. This chapter highlights the sources of MNPs in the environment. It also discusses their effects on the environment and ecosystem, soil organisms, human health, plants, marine fish, and aquatic organisms. Finally, the status of research in this field is focused. By analyzing this recent research, the authors find out some research gaps and indicate future research areas for MNPs.

2 Sources of MNPs

The amount of plastic pollution has been consistently rising over the last several decades, and researchers are working very hard to understand how microplastic pollution works and how it enters the natural ecosystem from urban areas. Most of the research is concerned with marine systems. Little attention is given to land-based micro-nanoplastics sources, despite having a great impact on the level of micro-nanoplastics pollution as a whole (Golwala et al., 2021). Though the manufacturing and use of plastics are mainly limited on land (Horton & Dixon, 2018), more attention is given to the marine ecosystem than the terrestrial environment when considering studies on microplastic pollution. Microplastics are widely distributed and found in the air, rivers and lakes, sediments, estuaries, oceans, and other environmental areas as a consequence of not having appropriate waste management and improper human disposal of plastics (Fig. 1).

There are mainly two types of sources for micro- and nanoplastics in the environment: primary sources and secondary sources. Secondary microplastics are created from the destruction of macro and meso-plastics via chemical, biological, and mechanical interactions, while primary microplastics are purposefully created in micro sizes for many different objectives (He et al., 2019). Primary microplastic sources include commonly used personal care products containing paint, microbeads, glitter, wastewater from washing, rubber from cities, vehicle tires, sewage sludge, and artificial turf. Because the number of vehicles is rising quickly due to urbanization, one of the most significant sources of microplastic is thought to be car tire wear in this modern era. Municipal wastes such as bottles and plastic bags, farming films, mulching material, microfibers produced from synthetic clothing, fishing wastes, and other relatively large plastic wastes are included in the secondary sources of microplastic (An et al., 2020).

The abrasion of tires from vehicles and traffic (Evangeliou et al., 2020), household and domestic products like cleaning supplies and cosmetics, fibers of synthetic origin from washing cloths and textiles (Boucher & Friot, 2017), coatings, paint, and activities leading up to painting are included as sources as inputs of micro-sized plastic to the terrestrial environment (Fig. 1). Improper waste management and direct littering, such as industrial spills and landfill site discharges, also contribute a major portion to the release of microplastics into the environment.

Plastics can enter the terrestrial environment as a result of agricultural operations, either through inappropriate bale twine and wrapping disposal or by the application of sewage sludge to the cultivated field (Corradini et al., 2019). For instance, in Europe alone, sewage sludge applications annually add between 125 and 850 tons of microplastic per million people to agricultural soils (Nizzetto et al., 2016).

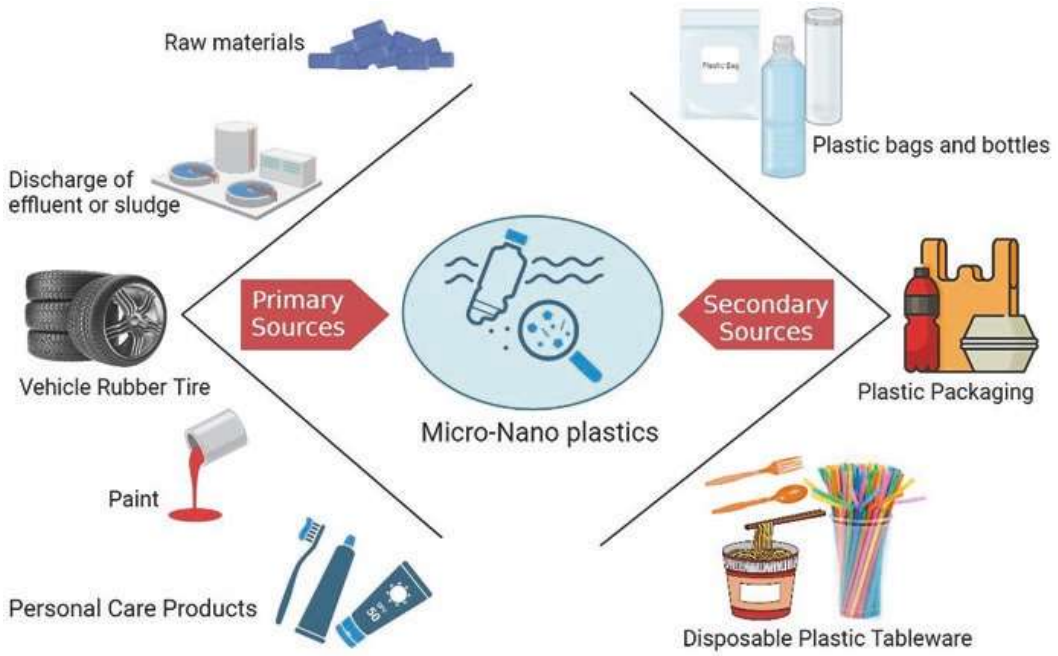

Fig. 1 Sources of MNPs in environment

Through wind transmission, air deposition, and surface runoff from neighboring areas, poor waste management or insufficient trash disposal act as sources of plastic in the aquatic environment (Xia et al., 2020).

2.1 Primary Sources

The rapid increase in the use of synthetic fibers in textile industries, microbeads from items for personal care, and cosmetics are significant primary microplastic sources worldwide (Fu & Wang, 2019).

2.1.1 Raw Materials

Granular-sized plastics or pellets with diameters of 2–5 mm and a uniform shape are used as raw materials in plastic production (Karlsson et al., 2018), which are frequently used in making different plastic products. These particles of plastic are commonly used in many aspects of day-to-day life, including household appliances, building materials, clothing materials, chemicals, and even agriculture. Besides, they are extensively utilized in the production of automotive, electrical, telecommunication, and medical instruments. Plastic pellets are persistent materials, which means that after entering the environment they degrade very slowly. They mostly affect human health because of their small particle size, easy consumption by fish and birds, and easy transmission down the environmental food chain (An et al., 2020).

There has been a rapid rise in the manufacturing of plastic particles in recent years due to their high demand. Unexpected consequences of this manufacturing include the potential release of microplastic particles into the surroundings during manufacturing, transportation, usage, storage, and recycling of plastic particles.

2.1.2 Wastewater

With the discharge of effluent or sludge, microfibers of plastic origin are released during clothing washing and go into the environment. According to certain research, the bulk of microplastics in the environment is plastic microfibers that may be discovered in rivers, oceans, and soil (Horton et al., 2017a, b).

2.1.3 Vehicle Rubber Tire

Among the main sources of micro- or nanoplastics in road dust, microplastics emitted by tires have the most effect. Air, soil, sewers, soil, and surface water are only a few of the locations where rubber particles from roadside motor vehicle tires can end up. With the increase in friction with the road, the rate of rubber particle emission from tires also increases (Vogelsang et al., 2019).

2.1.4 Paint

Typically, pigments, solvents, fillers, and trace amounts of useful ingredients make up paint. Numerous studies show that applying a layer of paint to a surface may cause the development of tiny particles of plastic, which can eventually be discharged into nature due to aging, abrasion, and erosion. So, paint is considered a major source of microplastics. Architectural coatings, such as paint that comes off of painted buildings, maritime coatings, automobile coatings, and road marking paints, are microplastics from all environmental sources (Wang et al., 2019).

2.1.5 Products for Personal Care

Microbeads are little pieces of plastic that have undergone processing to become microscopic. In order to produce cosmetic effects including exfoliating, whitening, washing, and the removal of dead skin, microbeads may largely replace the synthetic pigments currently found in personal care products. Toothpaste, UV protection lotion, shower gel, and hair dye are just a few products that contain microplastic beads. Because of their tiny dimensions, slow fragmentation, and insolubility in water, when washing wastewater enters the sewer system, microbeads do enter. The sewage treatment technology struggles to properly remove plastic microbeads. Due to the fact that sewage sludge is often used in agriculture, these microbeads end up in the environment.

2.2 Secondary Sources

Weathering and degradation of large microplastic materials under various environmental conditions are the main sources of secondary microplastics (Peng et al., 2020).

2.2.1 Plastic Bags and Bottles

Plastic bottles are a type of container made of materials like polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) and bags composed of various plastic raw materials are referred to as plastic bags. Plastic bottles are often used as disposable containers for storing liquids or solids such as drinks, agricultural veterinary drugs, culinary oils, sauces, dried fruits, and honey. Particularly in some remote areas, clean drinking water is occasionally provided in plastic bottles and bags. Currently, almost one million plastic bottles are sold per minute all over the world. Around the world, more than 5 trillion plastic bags are used annually. About 100 million plastic bags are used by customers each year in the USA (An et al., 2020).

2.2.2 Plastic Packaging

Plastic packaging is used to wrap an object to protect its original quality as well as its value during transit, storage, and distribution. Plastic packaging materials account for around 25% of the packaging materials globally, making up about 39.7% of the total amount of plastic manufactured.

2.2.3 Tableware Made of Disposable Plastic

Utensils composed of resin or similar thermoplastic substances that are used for dining or other comparable situations are referred to as disposable plastic utensils in general. Disposable plastic dinnerware includes things like lunchboxes, knives, dishes, saucers, drinking straws, containers, spoons, forks, cups, and cans; however, long-term food packaging and other similar products are not included. Polystyrene is used in the production of food service goods and packaging materials, including foam cups, instant noodle packets, and fast food cartons. Plastic tableware can enter soil, sewers, oceans, and other areas if it is not disposed of properly. Over time, it partially degrades and becomes an environmental pollutant.

3 Effects of MNPs

3.1 Effects on Environment and Ecosystem

Environmental contamination by micro-nano-plastics is being considered a new danger to ecosystem health and biodiversity. Small particles of plastic are the consequence of breaking down plastic waste that has been left in the environment, such as on land or in water bodies. Due to their capacity to accumulate in the food chain and their potential to have harmful impacts on human health, microplastics are now considered an important environmental issue. The majority of microplastic particles are produced and used on land, but their accumulation affects both land and water (Mai et al., 2018). Different types of MNPs have different effect on environment. Table 1 summarizes the size, polymer types, and shape of MNPs.

Evidence indicate that microplastics may have detrimental effects on marine ecology, especially in isolated and vulnerable regions because they have spread across the sea (Avio et al., 2015). About 4- to 23-fold greater microplastic contamination was found in land ecosystems than ocean ecosystems (Horton et al., 2017a, b). Threats that microplastics pose to aquatic systems are often linked to the chance that aquatic organisms will eat them, that they will act as solid surfaces for the transfer of contaminants or that they could cause physical damage.

Scientists, decision-makers, managers involving natural resources, the media, and the general public have recently shown a great deal of interest in the issue of

Table 1 MNPs properties based on polymer type, shape, and size

Polymer type	Size	Polymer shape
Low density polyethylene (LDPE), Polyethylene terephthalate (PET), polypropylene (PP), Polystyrene (PS)	0.5 mm – 250 nm	Pellet, fiber, line, grainy, foam
High density polyethylene (HDPE), Polyethylene terephthalate (PET), polypropylene (PP), Polyurethane (PU), Poly Vinyl Chloride (PVC)	<2 mm – 480 nm	Fragment, film, globule, line
Polycarbonate (PC), polypropylene (PP), Poly Vinyl Chloride (PVC), Polystyrene (PS)	<5 mm – 10 nm	Fragment, foam, film, fiber,
Polyethersulfone (PES), Polyethylene terephthalate (PET)	0.1 mm – 76 μm	Fragment, filament, globule
Polyethylene terephthalate (PET), polypropylene (PP), Polystyrene (PS)	0.3 mm – 50 μm	Fragment, film, filament, globule
Poly Vinyl Chloride (PVC), Polystyrene (PS), Polyethylene terephthalate (PET)	0.5 mm – 1 μm	Fragment sheet, foam, fiber,

plastic particles, which is a ubiquitous environmental concern and may also be a substantial human health issue (Prata et al., 2021). Either directly as primary microplastics or indirectly as secondary microplastics, microplastics can invade terrestrial ecosystems (Waldman & Rillig, 2020).

Plastic pollution is complex and follows a critical environmental cycle (Bank & Hansson, 2022). The numerous polymers and additives that make up microplastics can affect their ability to influence living things. The observed effect includes impacts on ingestion, population dynamics, feeding behavior, reproduction, metabolic function, and other contaminant interactions (Kögel et al., 2020).

Micro-nanoplastics have an impact on carbon dioxide (CO_2) emissions as well as in the process of carbon conversion and carbon sources, largely via altering microbial community makeup, gene abundance, and enzyme performance. Microplastics affect nitrogen fixation, nitrogen sources, ammonification, nitrification, and denitrification by changing the number of genes, the activity of enzymes, and the makeup of microbial communities. Microplastics can also influence phosphorus content and phosphorus conversion processes via uplifting enzyme production and altering the genetic makeup of microbial populations (Wang, 2022).

There exist clear research gaps on the impacts of both micro-nanoplastics in particular taxonomical groups, despite the fact that a variety of ecotoxicological effects brought on by exposure to plastic particles have been observed in a range of organisms. Ecotoxicological studies on microalgae showed that microplastics caused a wide range of biochemical and cellular or sub-cellular effects, like changing gene expression, which is involved in metabolic pathways, slowing photosynthesis, and stopping growth (Mao et al., 2018). Changes in microbial activity may also affect critical ecosystem functions such as the carbon cycle, nitrogen cycle and nutrient cycling (Green et al., 2017). Microplastic contamination can have an effect on an organization's higher level and affect the performance of an organism (such as reproduction and feeding). These changes may have an effect on the total

population and have an impact on the ecosystem. It is highly challenging for any environmental contaminant to establish a direct connection between impacts at the base of the biological hierarchy and consequences on ecosystems (Galloway et al., 2017).

The combined effects of microplastics can change the soil's structure and texture physio-chemically, which has an impact on the water cycle, ecosystem function in land systems, and a number of feedbacks in plant-soil interactions (Zheng et al., 2016). Changes in the hydrology of soils caused by microplastics may affect a variety of soil organisms. This could affect important symbiotic relationships in terrestrial ecosystems, such as N-fixing and mycorrhizal associations (de Souza Machado et al., 2018).

Nanoplastics might accumulate in land and food webs, though no conclusive evidence has been found yet. The most established way for particles to enter the body is through the intestinal lymphatic cells, which can be found in small rodents, humans, and dogs. Ingestion of microplastics by accident could be very harmful to the well-being of individuals. The majority of big plastic particles are not poisonous enough to kill. However, exposure to, consumption of, and uptake of microscopic microplastics may be hazardous and serve as a new source of very long-term environmental stress.

Microplastics may not be the most dangerous (lethal or sublethal) hazard in the environment on their own. However, there are persistent tendencies in the past, present, and future that indicate an increase in nearly permanent plastic contamination of the world's natural habitats (Geyer et al., 2017). Contamination from microplastics may have significant effects on the biodiversity of continental systems, which is almost entirely unconsidered (de Souza Machado et al., 2018).

Despite the increasing recognition of the environmental risks posed by micro-nanoplastics, there are clear research gaps in understanding their specific impacts on particular taxonomical groups. The consequences of microplastic exposure on microalgae and soil organisms have not been thoroughly studied, despite the fact that ecotoxicological effects have been seen in a variety of organisms. Furthermore, nothing is known about the possible long-term effects of microplastic exposure on continental ecosystems and biodiversity. To fully comprehend and reduce the effects of the pollution of MNPs on the environment and human health, it is essential to eliminate these discrepancies in knowledge.

To sum up, the health of ecosystems and biodiversity are significantly threatened by the presence of micro-nanoplastics in the environment. Their vast accumulation in ecosystems on land and in the sea, as well as their capacity to transport toxins up the food chain, requires immediate attention. The detrimental impacts on marine life, soil structure, and other physiological and environmental systems highlight the urgent need for in-depth research and proactive steps to reduce the growing plastic pollution and protect the ecological balance of the world.

3.2 *Effects on Human Health*

Microplastics, originating from various sources, including industrial waste, runoff, biomedical products, and everyday items such as bottle caps, sugar, plastic tea bags, and cosmetics, have raised alarming concerns about their impact on human health (Blackburn & Green, 2022). MNPs have a slower degradation rate due to photo and thermo-oxidative processes, posing a long-term threat to the environment and human health (Sangkham et al., 2022). Individuals are exposed to MNPs through inhalation, dietary consumption, and skin exposure (Fig. 2).

Microplastics that enter the body through ingestion can also cause various health issues, including apoptosis, necrosis, DNA damage, inflammation, and cancer (Dai et al., 2022). Food is often stored in plastic containers, susceptible to degradation from external factors like temperature. Plastics can break down under favorable temperatures and mix with food. Ingesting microplastics-contaminated food can lead to plastic particles storage in our digestive system, causing inflammation or physical harm to the tissues. A study has shown that plastic tea bags release a substantial amount of MNPs when brewed in hot water, which humans can directly ingest, contributing to chromosome alteration, weaker immunity, infertility, and obesity (Zhou et al., 2019). After infiltrating into human bodies, microplastics can generate reactive oxygen species (ROS) and disrupt cellular redox balance, leading to cellular damage and dysfunction.

Consumption of seafood, which is a good source of nutrients such as omega-3 fatty acids and minerals such as zinc, can also lead to microplastic ingestion,

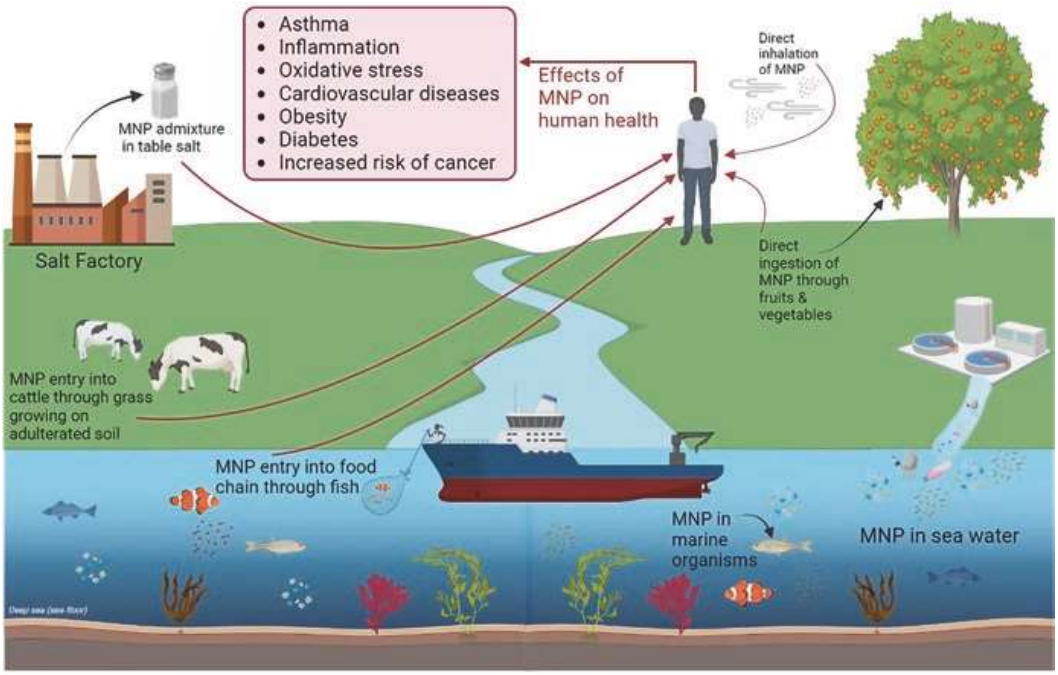

Fig. 2 Entry points for MNPs into the human body and their effects

resulting in neurological diseases. Acetylcholinesterase is an enzyme that breaks down acetylcholine, an important neurotransmitter for memory. Microplastics can inhibit the activity of acetylcholinesterase, leading to learning and memory problems. The microscopic size of the microplastics allows them to enter the bloodstream by passing through intentional walls. By entering the bloodstream, microplastics can disrupt the natural antioxidant defense of the body, which results in oxidative stress. Hence, microplastic particles can release chemicals that are detrimental to human bodies which eventually lead to inflammation. Inflammation, if persisting for a long time, can contribute to diabetes and cardiovascular diseases. Additionally, aquatic organisms consume microplastics by ingesting contaminated food materials, which can be transferred to higher levels of the food web, even to humans (Walkinshaw et al., 2020). Due to this trophic transfer, even organisms at higher levels can be affected by growth inhibition and morality from ingesting organisms that live at lower levels.

Inhalation of household and industrial dust is considered one of the prominent pathways of consuming microplastics. According to human exposure estimates, inhalation mainly exposes adults to microplastics as they migrate frequently (Bank & Hansson, 2022). After accumulating in the respiratory system through inhalation, microplastics can alter the immune system, leading to an inflammatory reaction. Plasticizers that are used in manufacturing cosmetics, such as bisphenol A (BPA) and phthalates, can lead to endocrine disruption, impact the reproductivity of humans and animals, and have potential carcinogenic properties that cause cancer and mutagenicity (Blackburn & Green, 2022). Microplastics can also absorb toxins such as epoxy resin, polyvinyl chloride (PVC), persistent organic pollutants (POP), and heavy metals from their surroundings. Hence, infection and disease-causing microorganisms and poisons can spread by attaching to nanoparticles. Upon inhaling, microplastics containing toxins can react with other compounds inside human bodies and lead to chronic health issues. Microplastic inhalation has also been linked to respiratory illnesses and increased cancer risk despite the prevailing belief that most microplastic particles can be removed from the respiratory system.

Although research on the specific health impacts of microplastics through skin exposure is still evolving, it is evident that microplastics can cause allergic reactions and skin irritation. Particularly, microplastics pose a severe threat to people living in urban landscapes, such as hospitals, garments, manufacturing industries, and markets. Microplastics have also been found in personal care products, such as cosmetics, which indicates women are more prone to be affected by microplastics compared to men. Microplastics that enter through skin can accumulate in the liver, kidney, and intestinal tract, affecting intestinal flora balance, intestinal function, and liver–lipid metabolism.

The health consequences of microplastics are a rising concern. Microplastics have the potential to disturb the endocrine system, compromise respiratory and gastrointestinal health, influence immune function, and trigger inflammation. Microplastic exposure can also lead to bioaccumulation, transfer of toxins, and food chain contamination. Limiting plastic product use and fostering environmentally responsible habits are crucial to addressing these risks. Further research is

imperative to fully comprehend microplastics' long-term impact on human health and devise viable solutions to this environmental threat.

3.3 Effects on Marine Fishes and Aquatic Organisms

Microplastics have been recognized worldwide in marine environments and are becoming more common as pollutants in water ecosystems such as rivers, lakes, and aquatic systems (Yuan et al., 2022). Plastic particles can harm aquatic organisms depending on their size, concentration, and length of exposure (Goncalves & Bebianno, 2021). The most common toxicity of microplastics is physical damage, specifically the hindrance of the digestive tracts of organisms, which in turn minimizes the amount of nutrients that can be absorbed by the body (Ma et al., 2019). Hence, microplastics can accumulate in the tissues and cells of organisms, interfering with their normal functioning, and can also weaken the defense mechanisms of marine animals.

The consumption of nondegradable microplastics by marine organisms can lead to their bioaccumulation within the food chain and result in both physiological and toxicological consequences, including oxidative stress, tissue damage, immune toxicity, and genotoxicity (Porcino et al., 2022). Humans dump plastic items into water bodies, including rivers, ponds, lakes, canals, etc. Plastic items thrown into water bodies undergo decomposition by microbial communities and are stored in the stomach of fish, which are consumed by humans.

Microplastics can have long-lasting effects on fish, including variations in gene expression related to their immune systems, tissue damage, changes in the quantities of antioxidants in their bodies, histological abnormalities in the intestines, intestinal blockage, behavioral changes, and lipid metabolism changes, alteration in swimming behavior, immune response, and capacity to avoid prey (Bhuyan, 2022). A study has indicated that fish containing microplastics and nanoplastics displayed elevated levels of AChE activity in their brain and amplified Lipid peroxidation (LPO) levels in their brain and muscle tissues (Barboza et al., 2020). LPO levels in the brain are a marker for oxidative stress, characterized by the disproportionate generation of free radicals relative to the body's capacity to counteract them.

Ships and other water vehicles can discharge oil even when equipped with wastewater treatment. Altered oil properties can create larger and more persistent oil slicks, affecting light penetration, nutrient availability, and dissolved oxygen levels in the water body (Yang et al., 2021). Hypoxia, which refers to low oxygen levels, arises due to fish mortality and has detrimental impacts on the ecosystem by causing oxygen depletion. At the same time, less mobile animals cannot move to areas with more oxygen and are often killed, resulting in a significant reduction in life in affected zones and a disturbed aquatic ecosystem.

Nanoplastic can also affect fish's ability to navigate, communicate, and locate predators by interfering with their senses of smell, eyesight, and hearing. Nanoplastic can transport harmful substances such as heavy metals, endocrine disruptors (EDCs)

and persistent organic pollutants (POPs), which can potentially permeate the tissues of marine organisms, particularly fish, resulting in adverse consequences. Nanoplastics can accumulate in fish tissues, decrease locomotion, change hormone levels, and interfere with physiological activities.

Small crustacean consumption of microplastics can cause population declines, while biomarkers in fish and bivalves have shown abnormal behavior, oxidative stress, and neurotoxic effects (Dioses-Salinas et al., 2019). Microplastic exposure has been observed to cause impaired growth and development in crustaceans such as copepods, amphipods, and shrimps (Zhang et al., 2023). Epibenthic copepod reproduction could be impacted by the presence of microplastics in ocean sediments (Nobre et al., 2022).

Additionally, Microplastics also have devastating impacts on aquatic plants, and they can affect plants directly or indirectly. Microplastics in aquatic environments can interfere with the photosynthetic rate and biomass production of aquatic plants by blocking light and disrupting the balance of chlorophyll-a and chlorophyll-b ratios (Li et al., 2020). The existence of microplastics in the soil or sediment in which aquatic plants thrive can alter their physical and chemical characteristics, thus impacting their capacity to absorb water and essential nutrients, as well as hindering their proper root establishment. Elevated levels of microplastic in aquatic plants can result in cell death and DNA damage that eventually can lead to impairment of development, growth, and reproduction (Mateos-Cárdenas et al., 2021).

A multifaceted approach is necessary to reduce the impact of microplastics on the marine ecosystem. One practical strategy could be reducing the amount of plastic waste entering the environment by promoting recycling and improving waste management practices. Another alternative could be building more wastewater treatment plants that are capable of filtering out microplastics from sewage and stormwater before they are discharged into water bodies.

3.4 Effects on Plants

The omnipresence of MNPs affects almost all life forms (Pantos, 2022) and plants are no exception (Rillig et al., 2019). MNPs can affect various aspects of plants in both positive and negative ways (Table 1). For example, photosynthetic pigment or chlorophyll content, seedling growth, nitrogen content of leaves, α-amylase activity, and root and shoot biomass are found to be affirmatively related in some studies. There are some adverse effects of plastic pollutants on the plant body, like altered root growth, oxidative damage, lowered photosynthetic activity, an inactive enzyme system, inhibited gene expression, and diminished biomass (Fig. 3).

MNPs can enter the plant vascular system simply by absorption. Plant root surfaces can absorb microplastic particles that range from 5 to 50 nm in size (Yu et al., 2022) and nanoplastics have a chance of being internalized into plant tissue (Yin et al., 2021). The permeability of nanoplastics is greater than that of microplastics as they are tinier, and for that reason, they can penetrate biological membranes more

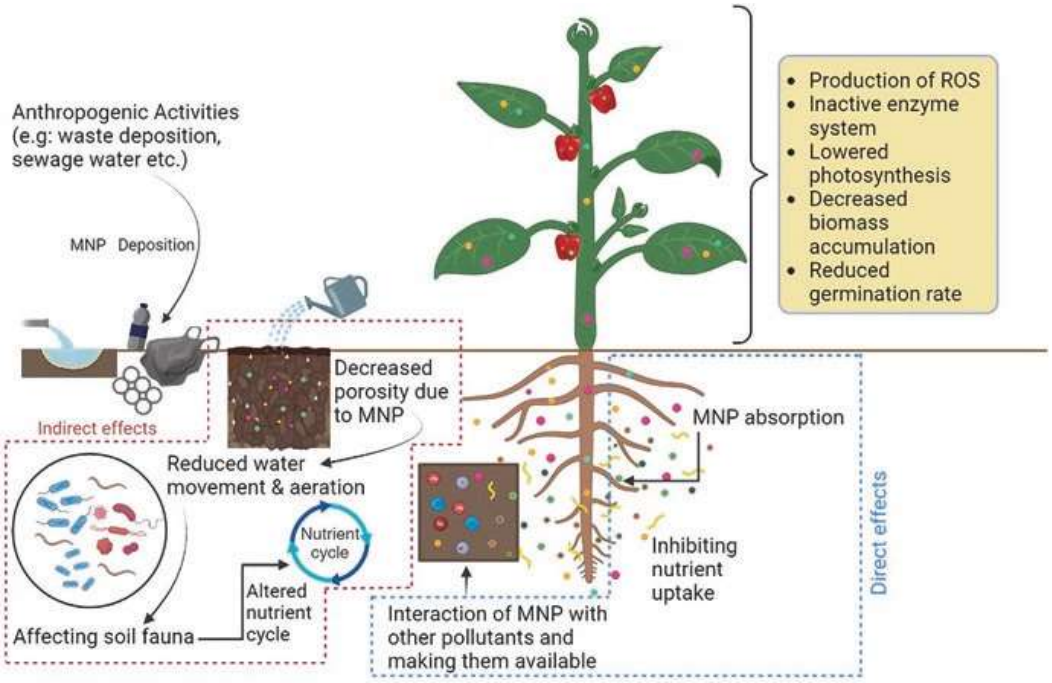

Fig. 3 Interaction of MNPs with the properties of soil and its impact on plant

easily (Bellingeri et al., 2020). Microplastics with both sharp and smooth edges directly affect plant root growth. Shorter root length is a visible effect of microplastic treatment in *Lemna minor* (Kalčíková et al., 2017). Sharp-edged microplastics mechanically damage plant roots with their rough surfaces. Nanoplastics, upon absorption, can cause oxidative damage and alter cell membrane structure (Rillig et al., 2019).

MPNs significantly reduce germination percentages in many plant species like *Lepidium sativum, Cicer arietinum, Trifolium repens, Lolium perenne, Impatiens balsamina.* Before germination, imbibition is a must for seed. During imbibition, plastic particles clog the seed surface, inhibiting germination, but upon plant growth, these plastic particles get moved from their previous position and the clogging effect is alleviated (Islam et al., 2023; Mondal et al., 2022).

Reactive oxygen species (ROS) are produced in excess compared to antioxidants, which causes oxidative damage. ROS production is a natural response of a cell to metabolism. But, in certain conditions, such as extreme temperature, excess light, drought, salinity, and heavy metal accumulation, ROS genesis is increased in response to stress. MNPs also have an impact on this ROS generation (Fig. 3). In nature, plants have a defense system to protect them from ROS, which is an antioxidant system. Many enzymes like glutathione (GSH), superoxide dismutase (SOD), catalase (CAT), and some nonenzymatic compounds like tocopherols, ascorbate (AsA), carotenoids, and phenolics serve as antioxidants. Studies show that MNP exposure can lead to the manufacture of ROS (Ekner-Grzyb et al., 2022). In onion, PS-NP significantly raises the H_2O_2 level when treated with 1000 mg/L concentration for 72 h (Giorgetti et al., 2020). In *Vicia faba,* MNPs decline CAT enzyme

activity, which eventually leads to oxidative damage (Jiang et al., 2019). A study conducted on wheat shows that MNPs combined with Cd impose a negative effect on the plant antioxidant system as they reduce Superoxide dismutase (SOD), Malondialdehyde (MDA) enzyme activity (Azeem et al., 2021). MNPs have a variety of effects on both terrestrial and aquatic plants, but additional research is needed to fully understand how different plastic kinds affect plants.

3.5 Effect of MNPs on Soil Organisms

MNPs are the major environmental and soil health hazards. MNPs affect a number of soil characteristics, including fertility, nutrient availability, and porosity, directly and indirectly (Bouaicha et al., 2022; Maddela et al., 2023), which determine the overall health of the soil.

MNPs change the soil's bulk density, porosity, and water-holding capacity, among other physical properties (Fig. 3) (Bouaicha et al., 2022). The types and concentrations of MNPs affect how they affect soil. Soil bulk density decreases as a result of microplastics such as PES (polyester) and PA (polyamide) fibers (Salam et al., 2023). The decrease in bulk density can be attributed to MNPs because they are not as dense as the soil matrix (Salam et al., 2023). Since bulk density makes it easier for water and other substances to move through the soil, improves soil aeration, and prevents compaction, it is one of the most crucial indicators of soil health. The bulk density of soil has a direct impact on its hydrological and agroecosystem processes (Y. Lu et al., 2019). Moreover, MNPs are hydrophobic in nature (colloidal MNPs). It raises difficulties in water movement through the soil column, which reduces the amount of available water to both microbes and plants (Wang, 2022). This may lead to imbalanced soil moisture levels, plant growth inhibition, and drought stress (Lu et al., 2021). MNPs can decrease soil porosity by occupying pore spaces (Rong et al., 2022). Decrease in porosity affects soil respiration rates and microbial activity by limiting water entry and airflow in the soil (Ben-Noah & Friedman, 2018). But sometimes microplastic pollution encourages soil cracking, which could lead to an increase in soil porosity. In addition, MNPs may disrupt soil aggregation processes by adhering to soil particles or changing microbial activity (Salam et al., 2023). Due to this disruption, soil stability is weakened, and erosion susceptibility is raised.

MNPs have a significant impact on soil fertility, nutrient absorption, and the toxicological composition of pollutants (Maddela et al., 2023). MNPs can influence the availability of nutrients by interacting with nutrient ions as they have adsorption ability. This can lead to an uneven intake of nutrients by plants as well as has an effect on the toxicological composition of contaminants of soil (H. Li et al., 2022). Microplastic contamination reduces soil pH by influencing soil bacteria that release hydrogen cations and also affects nutrient cycling as it declines soil microbial population (Lu et al., 2021). Poor soil quality, change in organic matter levels, and nutrient availability affect soil fertility (Medyńska-Juraszek & Jadhav, 2022).

MNPs influence soil microbial population. It disrupts microbial breakdown processes and declines microbial diversity (Elbasiouny et al., 2022; Maddela et al., 2023). The disruption of microbial diversity has the potential to have an impact on soil health and ecological balance. Substrate-induced respiration (SIR) rate reduces drastically with the addition of MNPs, indicating changes in the function of the soil microbial community (Salam et al., 2023). Plastic pollution might potentially reduce enzyme activity (Yu et al., 2020) which may contribute to the reduction in soil respiration. It is a quite alarming aspect as enzymatic processes used by microorganisms can break down MNPs, preventing their buildup in soil. The properties of MNPs, microbial species, soil factors, and ambient circumstances impact the biodegradation process.

Altogether, MNPs constitute a serious danger to soil health as well as the ecosystem due to their effects on soil characteristics, fertility, nutrient availability, and microbial activity. To protect soil ecosystems and ensure long-term sustainability, it is crucial to understand the effects of MNPs. It is essential to develop effective mitigation strategies which will ensure the long-term health of soil ecosystems.

4 Present Status of MNPs-Related Research

Using the latest instruments of analytical chemistry, researchers are trying to discover the right analytical procedures to describe and quantify the total amount of MNPs in water samples. Based on forensic investigation of microplastics from sediments, the proportions of polyester and acrylic fibers used in everyday apparel approximated those observed in locations that receive sewage discharges and sewage effluent. Based on research using wastewater from residential washing machines, one garment can yield close to 1900 fibers per wash. Up to 360 million tons of plastic products were produced annually in 2018, and it is anticipated that 500 million tons will be produced in 2025, according to statistics (Huang et al., 2021). Nearly 75% of all plastic manufactured ends up as waste, and 87% of solid waste from uncontrolled landfills that were improperly managed, leaks into the environment, causing plastic pollution.

Oceans are estimated to receive 4.8 to 12.7 million tons of the 2.5 billion tons of trash of solid origin created each year, of which coastal countries contribute up to 275 billion tons of plastic. (Jambeck et al., 2015). The North Pacific Ocean's Great Pacific Garbage Patch, which covers over 600 km^2, is recognized as the biggest landfill for plastic in the world (L. Lebreton et al., 2018).

The majority of studies on microplastics or nanoplastics focus on problems related to their presence, characterization, absorption by organisms, and impacts on fate and transport. Though assessing MNP's quantity, density, and distribution in the aquatic environment is very difficult because of their spatial as well as temporal fluctuation brought on by ocean currents and seasonal cycles, microplastics are considered to make up a significant portion of marine trash (Wang et al., 2021).

The research on microplastic pollution in sea surfaces (Anderson et al., 2017), surface waters (La Daana et al., 2017), and sediments (Lots et al., 2017) has increased sharply. These studies mainly focus on examining the geographical distribution and abundance of microplastics as well as classifying these artificial substances according to their many forms, dimensions, colors, and shapes.

The research field's focus has been on identifying the composition of microplastics to determine their probable sources (Lo & Chan, 2018). In the samples obtained from the bottom water of the Irish Continental Shelf, fibers were identified as the primary source of microplastic contamination (85%) (Martin et al., 2017). Every year, over two million tons of microfibers are discharged into the ocean (Boucher & Friot, 2017). Due to the toxicological concerns connected with these tiny particles, microplastic uptake by marine creatures is a developing concern. Numerous studies have shown microplastic consumption by finding various particles of polymers in the intestines and stomachs of many creatures, including zooplankton, shellfish, corals (Reichert et al., 2018), fish (Jabeen et al., 2017), and marine mammals (Nelms et al., 2018).

The Ganga River Catchment comes in second with an annual release of 0.12 million tons of plastics, next to the Chinese Yangtze River's impact of roughly 0.33 million tons of plastics, based on an empirical global model, that estimated that the ocean receives between 1.15 and 2.41 million tons of plastic through streams and that twenty Asian rivers contribute 67% of the world's marine plastic pollution (Lebreton et al., 2017). The sediments of the Ganga were incredibly rich in microplastics, with a mass ranging from 11.48 to 63.79 mg/kg and a numerical quantity of 99.27 to 409.86 items/kg, in accordance with the ICAR-CIFRI study at seven sites along the river, including Buxar, Nabadwip, Patna, Bhagalpur, Barrackpore, and Frazergunj (Sarkar et al., 2019).

Even while research on MNPs in the aquatic environment is expanding, there is still a significant research gap regarding the precise toxicological effects of MNPs on marine animals. While research has shown that MNPs are present and abundant in a variety of marine habitats, little is known about the potential trophic transfer and health effects of MNPs within marine food chains. In order to properly understand the possible hazards and long-term environmental effects of MNP contamination, more research must be done on the effect of MNPs on human health, particularly in terms of MNP consumption through food sources and water.

According to extensive research on the subject, there is growing concern about the prevalence and effects of MNPs in aquatic habitats. Plastic contamination poses a severe threat to marine ecosystems due to increasing plastic production and insufficient waste management. In order to address this rising contaminant and protect the ecosystem, it is essential to understand the composition, distribution, and toxicological impacts of microplastics.

5 Research Gaps and Future Works

Although MNPs are ubiquitous in nature, the research field related to MNPs is considerably novel. There are some research gaps in this field. The following aspects should be taken under consideration to fill the remaining voids:

- MNPs used in the experiments are spherical in shape, but microplastics derived from fragmentation are more like fibers (McIlwraith et al., 2019). These fiber-like or non-spherical nanoplastics are more difficult to come by. This has a significant impact on studies that measure the phytotoxicity that plastic particles impose.
- The absorption capacity of aged plastic particles is greater than that of primary MNPs (Mao et al., 2022). Aged plastic particles affect different things, especially plants and soil. As microplastics age, they undergo fragmentation and produce nanoplastics.
- MNP studies are more confined to aquatic organisms. Terrestrial plants play a key role as producers. Recently, this field has been getting attention, but an extensive area of terrestrial plastic pollution is yet to be explored.
- Current researches are more focused on individual ecosystem and mostly toxic effects of MNPs on organisms and environmental chemistry of MNPs. But a more holistic approach should be taken, ensuring inter disciplinary measures as MNPs have complex interactions among ecosystems.

6 Conclusion

Among other pollutants, MNP pollution is recognized as a significant contaminant since it lasts longer in the environment. The sustainability of environmental, global, social, and economic systems is threatened by MNPs contamination. In the past 50 years, the manufacture, usage, and disposal of plastic, particularly single-use plastic packaging, have multiplied 20-fold. Many single-use plastic products are difficult to recycle or can only be recycled so many times before ending up in the trash.

This chapter mainly discusses the significant effects of MNPs on the ecosystem, environment, human health, aquatic organisms, plants, and soil. Environmental contamination by MNPs poses a new threat to ecosystem health and biodiversity due to their accumulation in the food chain and potential harm to human health. MNPs' harmful impacts on marine life, soil structure, and physiological systems highlight the urgency of research and proactive measures to reduce plastic pollution. MNPs also affect human health through ingestion, inhalation, and skin exposure, leading to various health issues including inflammation, endocrine disruption and cancer. The presence of MNPs in water bodies affects aquatic organisms, plants, and soil, altering nutrient cycles, microbial populations, and ecosystem functions. This chapter provided an overall summary of the status of MNP-related research.

Besides, this chapter also found out some major research gaps regarding MNPs, including the influence of aged particles, the study of nonspherical MNPs, terrestrial pollution implications, and comprehensive ecosystem interactions. To solve the problems associated with MNPs, focus must be on a holistic approach to minimize those gaps.

Governments, businesses, and consumers have all made ambitious attempts to reduce plastic wastes, but these efforts have fallen behind the unsustainable rate at which plastic is being produced and used. Extreme efforts are needed to overhaul the global plastics value chain and achieve zero plastic waste in order to address the complex global problem of MNP contamination. Beyond laws and changes generated by a policy, particular measures are needed to accomplish this. All the people around the world should come forward from their respective positions to reduce pollution and the use of plastics.

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